LOW NOISE BALANCED AMPLIFIER

REFERENCE TO CO-PENDING APPLICATIONS

The present application is a continuation in part of United States patent application serial no. 09/759,968 filed on January 13, 2001 and entitled Low Noise Balanced Microwave Amplifier.

TECHNICAL FIELD

The present invention discloses low noise balanced microwave amplifiers and more particularly with balanced amplifiers having an input coupler as part of the noise-matching network and with balanced amplifiers.

BACKGROUND

It is presently known to use a low noise balanced amplifier (LNBA) comprising an input 3-dB-90° coupler, two identical low noise single-ended amplifier (LNSA) in each branch, and an output 3-dB-90° coupler. Typically, each LNSA is connected to each output port of the input coupler with the output port impedance to be the nominal value, which is 50-Ohm. Each LNSA comprises in series an input noise matching network, an active gain device, and an output-matching network. The input noise-matching network converts the nominal source impedance of 50 Ohm to the pre-determined optimum noise source impedance for the active gain device.

Comparing to a single-ended low noise amplifier, a low noise balanced amplifier offers following advantages: 1) to obtain the minimum noise performance and the good return loss at the same time at the input; 2) to have better stability; 3) to have improved

output radio frequency (RF) power level; 4) to have better intermodulation performance; and 5) to have redundancy. However, besides higher cost, a LNBA, generally offers higher noise figure than a LNSA because of the insertion loss of the input 3-dB-90° coupler. For example, a typical 0.20 to 0.40 dB insertion loss is observed for an input 3-dB-90° coupler at 1.90 GHz PCS frequency. The total noise figure of 0.70 to 0.90 dB is, taking into account the 0.2 ~0.4 dB insertion loss of the input coupler, resulted for a PCS LNBA if the active gain device such as a transistor has a typical noise figure of 0.30 dB and the input noise-matching network has an insertion loss of 0.20 dB.

A LNBA is widely used in telecommunications such as in a cellular phone base station because of the advantages mentioned above. However, lower noise figure is the key that determines the receiving sensitivity of the system. This is especially important to a cellular phone base station. A base station having lower noise figure provides wider coverage, increasing the battery life of a handset, and reducing the RF radiation exposure to a handset user.

It is presently known that the transmitting power of a handset is limited mainly by the battery capacity and the physical size. Higher sensitivity of the base station can receive weaker signal transmitted from a handset and thus coverage will be increased.

It is presently known that a base station sends a control signal to reduce the transmitting power of a handset if the base station detects the stronger signal (better signal-to-noise ratio) when the handset user is close to the base station. The transmitting power of a handset can be further reduced because of the higher sensitivity of the base station. Then, longer battery life and lower RF transmitting power are resulted.

It is presently known that the typical noise figure of a best LNBA is in the range of 0.70 dB to 1.0 dB up to 5 GHz frequency band at room temperature. 0.50 dB or lower noise figure of a LNBA is highly desired.

It is presently known that low noise monolithic microwave integrated circuit (MMIC) amplifiers have been widely used, especially in higher frequency bands. A low noise MMIC has the advantage of the small size with the drop-in simplicity in applications because the input and output ports of the MMIC are matched to the nominal

impedance such as 50-Ohm. In other words, the design of the input and output matching networks are not needed using a low noise MMIC amplifier. However, a low noise MMIC amplifier trades off its noise performance for the input matching performance.

It is presently known that low noise MMIC amplifiers have emerged in the frequency 10 GHz or above, well extended into millimeter wave bands. These low noise MMIC amplifiers, using integrated GaAs technology, offer miniature size with drop-in feature. However, the noise figure is in the range of 2.0 dB to 4.0 dB from 20 GHz to 40 GHz frequency range.

A low noise figure amplifier having a noise figure in 1.0 dB or below is desired in 20 GHz to 40 GHz ranges.

SUMMARY

One aspect of the present invention is a balanced amplifier having an integrated coupler and impedance matching scheme. Impedance has a resistive component and a reactive component. The balanced amplifier comprises first and second active gain devices. Each of the first and second active gain devices has a noise source impedance. A coupler has an input port, a first output port in electrical communication with the first active gain device, and a second output port in electrical communication with the second active gain device. The coupler has a first transmission line arrangement between the input port and the first output port, and a second transmission line arrangement between the input port and the second output port. The physical structure of the first and second transmission line arrangements matches at least one impedance component of the noise source impedance of the first and second active gain devices, respectively, without an impedance matching network being positioned between the coupler and the first and second active gain devices.

Another aspect of the present invention is a method of amplifying an electrical signal. The method comprises inputting an electrical signal into a coupler; conducting the signal along a first transmission line arrangement to a first output port, the first

transmission line having an impedance; conducting the signal along a second transmission line arrangement to a second output port, the second transmission line having an impedance; passing the signal directly from the first output port to a first active gain device, the impedance of the first output port substantially matching the noise source impedance of the first active gain device; and passing the signal directly from the second output port to a second active gain device, the impedance of the second output port substantially matching the noise source impedance of the second active gain device.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of a balanced amplifier according to the prior art.

Figure 2 is a schematic diagram of each of two identical single-ended amplifiers contained within the balanced amplifier of Figure 1.

Figure 3 is a schematic diagram of a 3-dB-90° Wilkinson coupler utilized within an input portion of the balanced amplifier of Figure 1.

Figure 4 is a schematic diagram of a 3-dB-90° Wilkinson coupler utilized within an output portion of the balanced amplifier of Figure 1.

Figure 5 is a schematic diagram of an impedance matching network used with the single ended amplifier of Figure 2.

Figure 6 is a graph illustrating the optimum noise source impedance and noise circles of a single-ended amplifier or a transistor as a function of frequency.

Figure 7 is a graph illustrating the classical noise matching impedance contour.

Figure 8 is a schematic diagram illustrating a Wilkinson coupler embodying the present invention.

Figure 9 is a graph illustrating the noise matching impedance contour of a coupler embodying the present invention.

Figure 10 is a schematic diagram illustrating a quadrature coupler embodying the present invention.

Figure 11 is a schematic diagram illustrating a Lange coupler embodying the present invention.

Figure 12 is a schematic diagram illustrating a parallel-coupled line coupler embodying the present invention.

DETAILED DESCRIPTION

Various embodiments of the present invention, including a preferred embodiment, will be described in detail with reference to the drawings wherein like reference numerals represent like parts and assemblies throughout the several views. Reference to the described embodiments does not limit the scope of the invention, which is limited only by the scope of the appended claims.

In general terms, the present invention relates to a low noise balanced amplifier configuration in which the mechanism for noise matching at the input of amplifiers is to integrate the noise source impedance matching network into the input coupler. In this configuration, the noise source impedance matching mechanism introduces less insertion loss between the input of the amplifier and the active gain device to improve the overall noise figure of the amplifier. Impedance is expressed as $Z = R + jX$, where Z is the impedance, R is the real or resistive component of the impedance, and X is the imaginary or reactive component of impedance.

The present invention also generally relates to the noise matching method of a balanced amplifier that comprises a low noise MMIC amplifier within each signal branch. In this configuration, the noise source impedance of the output ports of the input coupler is selected close to the optimum noise source impedance of the MMIC to reduce the noise figure of the LNBA instead of merely using a nominal impedance such as 50 Ohms. Also in this configuration, the load impedance of the MMIC is chosen for the best intermodulation performance instead of the nominal impedance such as 50 Ohms.

Before describing the present invention, it will be helpful to review the design of a conventional microwave balanced amplifier and the disadvantage inherent in it. Figure 1

illustrates a low noise microwave balanced amplifier in accordance with the prior art. An input microwave signal **105** is applied to an input port **101**, which signal travels to an input coupler **100**, which in one possible embodiment is a 3-dB-90° coupler. A portion of the input signal passes through the coupler **100** to a one single-ended amplifier **102a**, and another portion of the input signal passes through the coupler 100 and is coupled to another single-ended amplifier **102b**. The outputs of the single-ended amplifiers **102a** and **102b** are transmitted to an output coupler **103**, which in one possible embodiment is a 3-dB-90° coupler. The output coupler **103** combines the amplified signals and transmits the combined signal to the output port **104**.

Figure 2 illustrates the circuit diagrams within each of the single-ended amplifiers **102a** and **102b**. Each of the amplifiers **102** includes an input matching network **111**, an active gain device **112**, and an output-matching network **113**. The input matching network **111** converts the output impedance of the coupler, which is typically 50 Ohms, to the required noise source impedance for the active gain device **112**.

Figure 3 schematically illustrates the coupler **100** in the input portion of the balanced amplifier, and Figure 4 schematically illustrates the coupler **103** in the output portion of the balanced amplifier. As illustrated, in one possible embodiment the input coupler **100** and the output coupler **103** are Wilkinson 90° couplers.

Referring to Figure 3, one possible embodiment of the Wilkinson coupler **100** has an input port **101** that sees a source impedance **129**, a first output port **126** with an output impedance of **127**, and a second output port **125** with an output impedance **128**. A signal path **120** extends between the input port and a node **205**. Identical quarter wavelength transmission lines **121a** and **121b**, whose characteristic impedance is $\sqrt{2}$ times the nominal impedances at the input port **101** and output ports **125** and **126** of the coupler **100**, have a first end that are connected to the node **205**. A resistor **123** with the resistance of 2 times the nominal impedance of the output port **125** or **126**, such as a 100-Ohm resistor, is connected between the second, opposite ends of each transmission line **121**. An additional quarter wavelength element **124** with the characteristic impedance of 50 Ohms extends between the second end of the transmission line **121a** and the output

port **125**. The additional quarter wavelength element **124** is a 90° phase shifter. The second end of the quarter wavelength transmission line **121b** communicates directly to an output port **126**. The two output ports **125** and **126** of the coupler have an output impedance such as 50 Ohms.

Figure 5 illustrates one type of structure that typically has been used to form the impedance matching network **111** between the coupler **100** and the active gain device **112**. The impedance matching network **111** is formed with a high-impedance transmission line that has an input node **110** at a first end and an output node **206** at a second end. The input node **110** is connected in series to either the quarter wavelength transmission line **124** at output port **125** or the quarter wavelength transmission line **121b** at output port **127** depending on the branch of the balanced amplifier to which the impedance matching network **111** is connected. The output node **206** is connected to the input of the active gain device **112**. The second end of the high impedance transmission line is shunted to ground **163** through an inductor **162**. The impedance matching network, looking into the output node **206**, has an impedance **164**.

Figure 6 is a Z-impedance Smith Chart **140** illustrating the optimum noise source impedance of a hypothetical, but typical, active gain device such as a GaAs FET transistor. The dashed-line **141** is the optimum noise source impedance as it varies with frequency. The counter clockwise direction along **141** indicates the frequency increase direction. For example, the point **144** is the optimum noise impedance at 880 MHz, and the point **145** is the optimum noise impedance at 12,000 MHz. Circles **143** and **142** are equal noise circles relating to the noise source impedances required for the active gain device to produce 0.25 dB and 0.50 dB, respectively, which are higher noise figures than the optimum noise figure. It is desirable to select the noise source impedance close to or equal to the optimum noise impedance of the active gain device **112**. In Figure 5, for exemplary purposes only, the noise source impedance that is close to or equal the optimum noise impedance is hypothetically set at point **144** at a given frequency.

Figure 7 graphically illustrates one noise matching impedance contour of the classical method. The source impedance **129,** as shown in Figure 3, is the nominal

impedance Z_0 that is labeled as **150** on the Smith Chart **140'**. The output impedances **127** and **128**, as shown in Figure 3, are located on the point **150** since **127** and **128** are equal to the nominal impedance Z_0. A certain insertion loss, however, is introduced because of the loss of the signal paths of **120** , **121, and 124**. The high impedance transmission line **161**, shown in Figure 5, transforms resistive component of the source impedance at the point **150** to the point **154** in Figure 7. Then, the shunt inductor **162**, or alternatively a shunt high impedance transmission line, is used to transform the reactive component of the impedance at the point **154** to the final predetermined noise source impedance at the point **151**, which is close to the optimum noise source impedance at the point **144** for the active gain device. Using the impedance matching network **111** introduces another insertion loss into the balanced amplifier because of loss in the signal paths of **161** and **162.** The total insertion losses from signal paths of the input coupler **100** and the impedance matching network **111** are directly added to the noise figure of the LNBA.

Figure 8 illustrates an integrated input coupler and the noise-matching network **207** that embodies the present invention. In the illustrated embodiment, the integrated input coupler and noise-matching network **207** is a Wilkinson coupler.

The integrated input coupler and noise-matching network **207** has an input port **101** that sees a source impedance **129**, a first output port **175** with an output impedance of **177**, and a second output port **176** with an output impedance **164**. A signal path **170** extends between the input port and a node **208**. Quarter wavelength transmission lines **171a** and **171b** have a first end that are connected to the node **208**. A resistor **173** is connected between the second, opposite ends of each transmission line **171**. An additional quarter wavelength element **174** is a 90° phase shifter and extends between the second end of the transmission line **171a** and the output port **176**. The additional quarter wavelength element **174** is a 90° phase shifter. The second end of the quarter wavelength transmission line **171b** communicates directly to the output port **175**. In one possible embodiment, the resistive component of the output impedance **164** is in the range from about 10 Ohms to about 500 Ohms.

The transmission lines can be formed with any type of electrical conductor that can be used to form a coupler. One example includes microstrips or other traces mounted on a substrate. In one possible embodiment, the substrate can be a material having dielectric properties and a grounding plane on the backside. Another example of a conductor is a coaxial cable, which has an inner conductor along its axis, a core that may have dielectric properties surrounding the conductor, a shield surrounding the core, and a jacket.

In one possible embodiment, the physical structure of the integrated input coupler and the noise-matching network **207** is modified to tune the impedance of the integrated input coupler and the noise-matching network **207** to match the input noise source impedance requirement of the active gain device **112**. The physical structure of the integrated input coupler and noise-matching network **207** can be changed in several different ways. One possible way to change the structure is to change the length, width, and thickness of the quarter wavelength transmission lines (or other conductors) **171** and **174**. Changing the physical dimensions of the quarter wavelength transmission lines **171** and **174**, will change both the resistive (i.e., real) and possibly the reactive (i.e., imaginary) components of the output impedance **164** or **177**.

Alternatively, the thickness or dielectric coefficient of the substrate on which the quarter wavelength transmission lines **171** and **174** are mounted can be changed. Changing the structure of the substrate changes the reactance of the transmission line, which in turn changes the reactive component of the impedance. In this embodiment, the quarter wavelength transmission lines **171a** and **171b** may not have identical structures, because their structure may be adjusted to alter their impedance. Similarly, if the transmission line is a coaxial cable, the thickness and dielectric properties of the core can be changed.

As illustrated in Figure 8, if modifying the structure of the integrated input coupler and the noise-matching network **207** does not adequately modify the reactive component of the impedance, a reactive component **178a** and **178b** can be arranged within the coupler to shunt to ground **163** the second or output end of the quarter wavelength transmission lines **174** and **171b**, respectively. In one possible embodiment,

the reactive components **178** are inductors if the desired reactance or imaginary component of the noise source impedance has a positive value and are capacitors if the desired reactance component of the noise source impedance has a negative value.

Different amplifiers used within the balanced amplifier can have different noise performance characteristics. For example, some amplifiers require only the resistive component of the noise source impedance, while other amplifiers require both the resistive and reactive components of the noise source impedance. As a result, different physical characteristics of the input coupler can be set to tune the resistive (real) and/or reactive (imaginary) components of the noise source impedance to match the corresponding resistive and/or reactive components, respectively, of the amplifier.

If only the resistive component of impedance needs to be matched, then the couple does not need to include the reactive components **178**. If it is desired to match the reactive component of the impedance the coupler circuit can includes the reactive components **178**, if the transmission lines themselves do not provide the desired reactance. The reactive components **178** are inductors if the desired reactive component of the impedance is greater than zero ($0 < jX$). The reactive components **178** are capacitors if the desired reactive component of the impedance is less than zero ($0 > jX$).

Within the structure illustrated in Figure 8 and described herein, the quarter wavelength transmission line **174** that functions as a 90° phase shifter has the predetermined characteristic impedance Z_{0s} instead of Z_0. The resistor **173** has the resistance value of 2 Z_{0s}. The characteristic impedance Z_{01} of quarter wavelength transmission lines **171** is determined by $\sqrt{2Z_0Z_{0s}}$.

Figure 9 illustrates the impedance matching contour of the integrated input coupler and noise-matching network **207** and the active gain device **112**. The source impedance **129,** as shown in Figure 8, is the nominal impedance Z_0 and is labeled as **150** on the Smith Chart **140"**. The output impedances **177** and **164** without the reactive components **178**, as shown in Figure 8, are directly transformed to the point **182**. Because the desired reactance component of the impedance has a positive value, shunt inductors, or alternatively a high impedance transmission lines, are used for the reactive components

178. The reactive components **178** form a shunt inductor to ground **163** and transform the impedance at **182** to the final predetermined noise source impedance at the point **151**, which is close to the optimum noise source impedance at the point **144** for the active gain device **112**. Only the insertion loss of the integrated input coupler and impedance-matching network **207** is introduced. The insertion loss that results from a separate impedance matching network is eliminated which improves the total noise figure of the balanced amplifier. For example, a 0.50 dB noise figure is obtained instead of a 0.70 dB noise figure at the PCS frequency band. Another advantages of the invention disclosed herein is that it enables balanced amplifiers having improved gain, noise figure, and return loss figures over a wider bandwidth. Yet another advantage is that eliminating a separate impedance matching network reduces the total number of circuit components and thus reduces the cost of the amplifier.

Although a Wilkinson couple is described above, other types of couplers can embody the invention as well. Referring to Figure 10, for example, one alternative embodiment integrates the impedance-matching network and a 3-dB-90° quadrature coupler. In this embodiment, a first transmission line **208** runs from an input port **110** to a first output port **209**. A second transmission line **210** runs to a second output port **211**. A resistor **212** is between the second transmission line **210** and ground **163**. Two quarter-wavelength transmission lines **213** and **214** extend between the first and second transmission lines **208** and **210**. In this embodiment, the physical structure of the quadrature coupler is adjusted to modify the output impedance at both the first and second output ports to be Z_{os} and match the required noise source impedance of the active gain device 112.

The physical structure of the quadrature coupler can be adjusted by changing the dimensions of the transmission lines **208, 210, 213,** and **214**, the thickness of the substrate on which the transmission lines **208, 210, 213,** and **214** are mounted, and/or the dielectric constant of the substrate material, and/or any other physical change that alters the impedance to the desired value. If the reactive component sill needs to be adjusted after they physical parameters are adjusted match the resistive component of the

impedance, reactive devices **178a** and **178b** can be arranged within the quadrature coupler and shunted between ground **163** and the first and second outputs **209** and **211**, respectively.

Yet another possible embodiment integrates the noise impedance-matching network into the Lange coupler as illustrated in Figure 11. In this embodiment, first, second, third, fourth, and fifth transmission lines **215**, **216**, **217**, **218**, and **221** run parallel to each other. Both the first and third transmission lines **215** and **217** have a first end connected to an input port **110.** The second end of the third transmission line **217** and first end of the fifth transmission line **221** are connected to the output port **220**. The second end of the first transmission line **215** is connected to the center of the third transmission line **217** through the jumper **222b**. The center of the third transmission line **217** is then connected to the second end of the fifth transmission line **221** through the jumper **222c**. The first end of the second transmission line **216** is connected to the first end of the fourth transmission line **218** through the jumper **222a**, and the second end of the second transmission line **216** is connected to the second end of the fourth transmission line **218** through the jumper **222d**. The second end of the fourth transmission line **218** is connected to the output port **219**.

In this embodiment, the physical structure of the Lange coupler is adjusted to modify the output impedance at both the first and second output ports to be Z_{0s} and match the required input noise source impedance of the active gain device **112**. The physical structure can be adjusted by changing the dimensions of the transmission lines **215**, **216**, **217**, **218**, and **221**, the thickness of the substrate on which the transmission lines **215**, **216**, **217**, **218**, and **221** are mounted, and/or the dielectric constant of the substrate material, and/or any other physical change that alters the impedance to the desired value such as the spaces between the transmission lines **215**, **216**, **217**, **218**, and **221**. If the reactive component sill needs to be adjusted after they physical parameters are adjusted to match the resistive component of the noise source impedance, reactive devices **178a** and **178b** can be shunted between ground **163** and the first and second output ports **219** and **220**, respectively.

Referring to Figure 12, yet another possible embodiment integrates the impedance-matching network and a parallel-coupled line coupler. In this embodiment, a first transmission line **224** is u-shaped transmission line has a first end connected to an input port **110** and a second end connected to ground **163** through a resistor **212**. A second transmission line **226** is u-shaped and has a first end connected to a first output port **228** and a second end connected to a second output port **230**. A central section **232** of the first transmission line **224** extends parallel to a central section **234** of the second transmission line **226** so that there is coupling between **232** and **234** sections .

In this embodiment, the physical structure of the parallel-coupled line coupler is adjusted to modify the output impedance at both the first and second output ports to be Z_{0s} and match the required noise source input impedance of the active gain device **112**. The physical structure can be adjusted by changing the dimensions and space of the transmission lines **232** and **234**, the thickness of the substrate on which the transmission lines **232** and **234** are mounted, and/or the dielectric constant of the substrate material, and/or any other physical change that alters the impedance to the desired value. If the reactive component sill needs to be adjusted after they physical parameters are adjusted match the resistive component of the impedance, reactive devices **178a** and **178b** can be shunted between ground **163** and the first and second ends of the second transmission line **226**, respectively.